Advances in Computer, Signals and Systems (2024)
Clausius Scientific Press, Canada

DOI: 10.23977/acss.2024.080508
ISSN 2371-8838 Vol. 8 Num. 5

Research on Cost Optimization of Fresh Commodities: An E-commerce Business Perspective

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Keywords: Fresh food E-commerce business, Inventory routing, Vehicle routing, Ant colony algorithm, Cost optimization

Abstract: With the high-quality economic development and per capita income of China improving significantly, the demand for fresh commodities surges unprecedentedly. This paper outlines two E-commerce channels for selling fresh goods and establishes an inventory routing problem model. Following this, two sub-problems are discussed, namely the transportation cost of the direct distribution channel as well as the warehousing cost and the deterioration cost of the channel involving offline distributors. To optimize transportation costs, a capacitated vehicle routing problem model is built, and the ant colony algorithm is improved by considering the load factor of distribution vehicles. The optimal route from a single distribution center to 50 customer sites is obtained by solving the specific example using MATLAB. To find the optimal solution for the warehousing cost and the deterioration cost, distribution periods are interpreted as piecewise functions. With one of the periods being selected, the summation of the aforementioned costs is obtained by setting parameter values. The inventory routing model and the improved ant colony algorithm proposed in this paper fully consider the actual selling conditions of fresh food e-commerce businesses, which results in more accurate analysis, thus providing a rational decision-making basis for the e-commerce businesses to analyze economic benefits.

1. Introduction

As the domestic economy experiences rapid development, the living standards of Chinese people have improved significantly and the market for health-benefiting fresh commodities expands subsequently. According to the statistics released by iiMedia Research, the size of China's fresh food market gradually expands and is estimated to reach CNY 630.2 billion by 2026. The Chinese government has issued a series of policies that encourage the transportation improvement and cold chain development of fresh food. In light of the 14th Five-Year Plan, China is to develop plans for the fresh food e-commerce businesses revolving around the fresh food logistics system and other aspects.

The economic cost consisting of fresh food logistics and warehousing is one of the major factors that influence the performance of fresh commodities. Nowadays, an increasing number of foreign and domestic scholars are showing concerns about the optimization of the aforementioned factors. The vehicle routing problem (VRP) model, inventory management model, and inventory routing model are among the most frequently used methods for such research. This section will review the current literature based on the three models.

Wang et al. established a dual-objective model with minimum logistics operation cost and number of vehicles used, solving the model via the non-dominated sorting genetic algorithm which was designed based on the Clarke-Wright savings algorithm [1]. Li et al. established a low-carbon distribution routing optimization model from the perspective of carbon emission [2]. Cao et al. established the objective function with minimum cost from the perspective of electric vehicle distribution, dividing cost into fixed cost, transportation cost, refrigeration cost, cargo damage cost, carbon emission cost, and charging cost, finding the optimal distribution route using the improved K-means clustering algorithm and the ant colony algorithm [3]. Huang et al. established a mixed-integer nonlinear programming model with product freshness as a constraint, among which the time satisfaction function depends on the customer's time window and the quality satisfaction function [4]. Wu et al. established a time-dependent VRP model of urban cold chain logistics on the basis of carbon emission, customer satisfaction, customer value, costs, and other factors, using piecewise functions to indicate vehicle speed at different stages [5]. Qian and Chen established a VRP model using the shortest route as the objective function and used the improved simulated annealing (SA) algorithm to solve the model [6].

Li and Wu proposed different management methods for commodities of different classes, considering the sales volume on the basis of the traditional method of ABC classification [7]. Wang et al. applied the Analytic Hierarchy Process (AHP) to sorting the fresh commodities hierarchically, modifying the ABC classification [8]. Hao et al. analyzed and evaluated multiple objectives of fresh food using AHP and proposed suggestions based on the results [9]. Ren studied JD Fresh, an e-commerce platform selling fresh food, finding that it utilizes shared warehousing and implements stringent management of product freshness. Furthermore, JD Fresh reduces the warehousing cost while maintaining sufficient product supply through zero-inventory coordination and other designs. Product freshness is guaranteed through stringent products selection, shelf life management, and other measures [10]. Ge and Han classified the inventory items using ABC classification, then applied the AHP approach for weighting fresh agricultural products with low varieties but a high percentage of inventory management costs hierarchically. Fresh agricultural products aforementioned were reclassified and sorted according to the calculated weights, providing a basis for more scientific, sensible inventory management strategies [11].

Wu et al. established an optimal dual-objective inventory routing model with minimizing the total costs of each section as the first objective and the lowest risks as the second objective [12]. Fan reviewed IRP under VMI mode, and summarized and classified its optimization algorithms [13]. Cavero et al. established a mixed-integer programming (MIP) model to solve the problems faced by companies in the oil and gas industry. It is a model that adapts complex products, diverse vessels, as well as long-term planning and vision [14]. Skålnes et al. presented the branch-and-cut embedded matheuristic to solve the IRP model [15].

2. Problem Description and Notation

2.1. Problem Description

Against the aforementioned backdrop, the research into the cost optimization of fresh commodities under different distribution channels is of great practical significance. First and foremost, due to perishability and other features of fresh food, temperature-controlled storage is required, which leads to higher costs as the storage time increases with the risk of deterioration. Additionally, the distribution route should be rationally planned to both reduce the transportation cost and satisfy the requirements of consumers.

As an intermediary platform between suppliers and customers, fresh food e-commerce businesses have diverse distribution approaches. The fresh commodities can be firstly distributed to the self-owned offline distributors for sale or be sold to first-tier customers, namely the fresh food retailers, who sell the commodities to the second-tier customers, namely individual customers. Alternatively, the fresh commodities can be directly distributed from the distribution center, namely the warehouse, to individual customers. Therefore, during the process, how to control the logistics transportation cost and minimize the warehousing cost are among the prominent issues that should be studied by the e-commerce businesses. This paper, from the perspective of fresh food e-commerce businesses, refers to both first-tier customers and second-tier customers as customers, which can be seen in Figure 1, and fully considers the distribution process to customers as well as the warehousing cost and deterioration cost of offline distributors. Aiming at minimizing the total costs of the three aforementioned factors, it establishes an IRP model by coordinating the VRP model and the inventory management model.

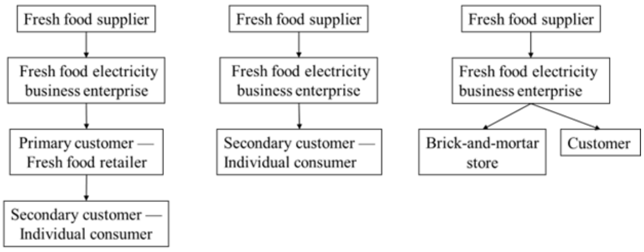

Figure 1: The distribution channel and simplified distribution channel of fresh food e-commerce

2.2. Model Notation

The description of each parameter and variable of this model is presented in Table 1, where F_t, $F_t(0)$, $F_t(1)$, θ, h_t, g_t, W_{2t}, W_{3t} are in the case of choosing the period $[t, t+1]$.

Table 1: Description of parameters and notations

Parameter	Description of notation	Parameter	Description of notation
i, j	Customer site	θ	The moment when the inventory is depleted
s_{ij}	Distance from Customer site i to Customer site j	h_t	Quantity demanded from offline distributors
Q	Maximum capacity of distribution vehicles	g_t	Replenishment quantity of offline distributors
d_i	Quantity demanded from Customer site i	u	Inventory cost per unit of offline distributors
m	Number of distribution vehicles	v	Deterioration cost per unit of offline distributors
n	Number of customer site	α	Fresh commodities deterioration rate of offline distributors
x_{ij}^k	0/1 binary variable If vehicle k visits Custom site i first, and then Customer site j, it is 1. Otherwise, it is 0.	W_1	Transportation cost
C	Maximum inventory capacity of offline distributors	W_{2t}	Warehousing cost
F_t	Inventory level of offline distributors at a specific point after the fresh commodities are distributed	W_{3t}	Deterioration cost
$F_t(0)$	The inventory level of distributors at the beginning	W	Total costs
$F_t(1)$	The inventory level of distributors at the end		

3. Model Building

3.1. Hypotheses

Regarding the aforementioned problems, a total of 11 hypotheses are proposed. The first hypothesis is that a single warehouse, namely a single distribution center has one and only one offline distributor. The second hypothesis is that the processes of distributing to the offline distributors and customer sites are independent of each other. The third hypothesis is that the sales process of offline distributors is cyclical and there is no interval between procurement and delivery. The fourth hypothesis is that only the condition when the inventory quantity meets the sales demand of offline distributors is considered, namely when $\theta \geq 1$. The fifth hypothesis is that the transportation cost only contains the distribution cost from the warehouse to each customer site. The warehousing cost refers specifically to the warehousing cost of offline distributors. The deterioration cost refers specifically to the deterioration cost of fresh commodities of offline distributors. The sixth hypothesis is that the time window constraints for distribution are dismissed. The seventh hypothesis is that the distribution vehicles keep traveling at a constant speed. The eighth hypothesis is that the transportation cost is solely related to the transportation route with minimum transportation cost representing the shortest total transport distance. The ninth hypothesis is that the path is symmetrical, and the distance from Customer site$i$ to Customer site$j$ equals that from Customer site$j$ to Customer site$i$.

3.2. Transportation Cost Analysis

According to the fifth and ninth hypotheses, the transportation cost is solely related to the transportation distance. To minimize transportation cost means to find the shortest transport route, namely a CVRP [16]. Therefore, the transportation cost W_1 can be expressed as follows:

$$W_1 = \sum_{k=1}^{m} \sum_{i=0}^{n} \sum_{j=0}^{n} s_{ij} \cdot x_{ij}^{k}, \tag{1}$$

Among them, i or $j = 0$represents the starting point, namely the distribution center (the warehouse). s_{ij} represents the distance from Customer site i to Customer site j , and x_{ij}^{k} represents the 0/1 binary variable, in which 1 means the vehicle k first visits Customer site i and then Customer site j, and 0 indicates any other conditions.

3.3. Warehousing Cost Analysis

According to the third hypothesis, a random period $[t, t+1]$is selected, and the offline distributors' inventory of fresh food e-commerce business is depleted at moment θ of this period, which can be expressed as follows:

$$F_t(\theta) = 0 \tag{2}$$

According to the IRP model of perishable products studied by Qin [17], the inventory level at moment p can be obtained:

$$F_t(p) = \frac{h_t}{\alpha}\left[e^{\alpha(\theta-p)} - 1\right], 0 \leq p \leq 1 \tag{3}$$

When $p = 0$, the inventory level of distributors at the beginning of the period $[t, t+1]$ can be obtained:

$$F_t(0) = \frac{h_t}{\alpha}\left(e^{\alpha\theta} - 1\right) \tag{4}$$

When $p = 1$, the inventory level of distributors at the end of the period $[t, t+1]$ can be obtained:

$$F_t(1) = \frac{h_t}{\alpha}\left[e^{\alpha(\theta-1)} - 1\right] \tag{5}$$

The inventory level at the moment $t+1$ after restocking:

$$F_{t+1}(0) = \frac{h_t}{\alpha}\left[e^{\alpha(\theta-1)} - 1\right] + g_{t+1} \tag{6}$$

After substituting *t* with *t*+1, the following equation can be obtained:

$$F_t(0) = \frac{h_{t-1}}{\alpha}\left[e^{\alpha(\theta-1)} - 1\right] + g_t \tag{7}$$

Based on Equations (4) and (7), the following equation can be obtained:

$$F_t(0) = \frac{h_t}{\alpha}\left(e^{\alpha\theta} - 1\right) = \frac{h_{t-1}}{\alpha}\left[e^{\alpha(\theta-1)} - 1\right] + g_t \tag{8}$$

The relationship between the inventory level at moment p within each period and the inventory level at the end of the preceding period, as well as the relationship between the quantity demanded and replenishment quantity for each period and the quantity demanded from the preceding period can be obtained together with Equation (3):

$$F_t(p) = \frac{\frac{h_t}{\alpha}(e^{\alpha\theta}-1)}{e^{\alpha p}} + \frac{h_t\left(\frac{1}{e^{\alpha p}}-1\right)}{\alpha} = \frac{F_{t-1}(1)+g_t}{e^{\alpha p}} + \frac{h_t\left(\frac{1}{e^{\alpha p}}-1\right)}{\alpha} = \frac{\frac{h_{t-1}}{\alpha}[e^{\alpha(\theta-1)}-1]+g_t}{e^{\alpha p}} + \frac{h_t\left(\frac{1}{e^{\alpha p}}-1\right)}{\alpha} \tag{9}$$

The inventory cost of offline distributors for the period $[t, t+1]$ can be obtained by finding the definite integral of Equation (3) over the interval [0,1] and then multiplying the unit inventory cost u:

$$W_{2t} = u\int_0^1 F_t(p) = \frac{u\cdot(h_t e^{\alpha\theta} - h_t e^{\alpha\theta-\alpha} + \alpha)}{\alpha^2} \tag{10}$$

3.4. Deterioration Cost Analysis

According to the aforementioned process, the deterioration cost can be obtained by finding the definite integral of Equation (4) over the interval [0,1] and then multiplying unit deterioration cost v and deterioration rate α:

$$W_{3t} = \frac{v\cdot\alpha\cdot(h_t e^{\alpha\theta} - h_t e^{\alpha\theta-\alpha} + \alpha)}{\alpha^2} = \frac{v\cdot(h_t e^{\alpha\theta} - h_t e^{\alpha\theta-\alpha} + \alpha)}{\alpha} \tag{11}$$

3.5. Model Establishment

The following IRP model is established in light of the above derivations.

Total cost = Transporation cost + warehousing cost + deterioration cost, which can be expressed as follows:

$$W = W_1 + W_2 + W_3 \tag{12}$$

The following objective function is established by selecting one specific period:

$$min \sum_{k=1}^{m}\sum_{i=0}^{n}\sum_{j=0}^{n} s_{ij}\cdot x_{ij}^k + \frac{u\cdot(h_t e^{\alpha\theta} - h_t e^{\alpha\theta-\alpha} + \alpha)}{\alpha^2} + \frac{v\cdot(h_t e^{\alpha\theta} - h_t e^{\alpha\theta-\alpha} + \alpha)}{\alpha} \tag{13}$$

Constraints are listed as follows:

$$\sum_{k=1}^{m}\sum_{j=1}^{n} x_{ij}^k = 1, \forall i = 1, \dots, n \tag{14}$$

$$\sum_{j=1}^{n} x_{0j}^{k} = \sum_{i=1}^{n} x_{i0}^{k} = 1, \forall k = 1, \dots, m \tag{15}$$

$$\sum_{j=1}^{n} d_j \cdot x_{ij}^{k} \leq Q, \forall k = 1, \dots, m, \forall i = 1, \dots, n \tag{16}$$

$$F_0(0) = g_0,\ F_t(0) = F_{t-1}(1) + g_t \tag{17}$$

$$h_0 \leq g_0, h_t \leq F_t(0) \tag{18}$$

$$F_t \leq C \tag{19}$$

$$F_t \geq 0, h_t \geq 0, g_t \geq 0 \tag{20}$$

The first four constraints are used for the CVRP model, among which Equation (14) ensures that each customer site will be visited, and only once. Equation (15) ensures that all the distribution vehicles must depart from the warehouse and eventually return to the warehouse. Equation (16) ensures that the total quantity demanded of customer sites along each distribution route will not exceed the maximum capacity of distribution vehicles. Equation (17) presents the inventory level at the beginning of each period (after restocking). Equation (18) ensures that the quantity demanded of offline distributors within each period will not exceed the inventory level. Equation (19) ensures that the inventory level for each period will not exceed the maximum inventory capacity of offline distributors. Equation (20) specifies the non-negativity of each variable.

4. Solution Output

4.1. Algorithm Design

In accordance with the second hypothesis, the problem can be broken down into two sub-problems based on two distribution channels. The channel through which the warehouse of fresh food e-commerce business directly distributes the products to customer sites can be viewed as an individual CVRP. It has been proved as an NP-hard problem [18]. Therefore, the heuristic algorithm is used to find solutions. To find the optimal route and minimize the transportation cost, the total distance should be the shortest while endeavoring to maximize the load factor. Hence, this study applies the ant colony algorithm to finding the optimal distribution path, improving the algorithm with the load factor being considered. Steps of the ant colony algorithm are shown in Figure 2.

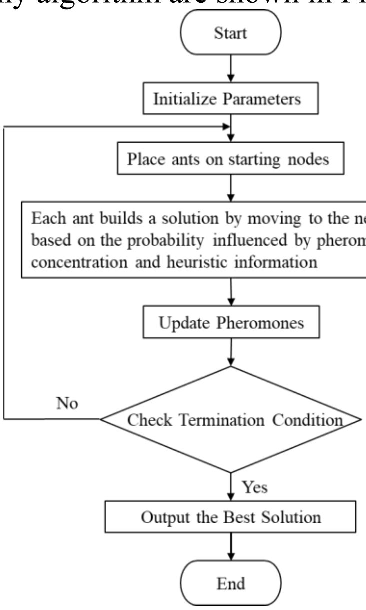

Figure 2: Flowchart of ant colony algorithm

According to the hypotheses, only warehousing cost and deterioration cost need to be considered regarding the channel through which the warehouse of fresh food e-commerce business distributes the products to offline distributors. In real-world conditions, values are assigned according to the operation conditions of offline distributors.

4.2. Example Analysis and Results

The optimal route problem of direct distribution from the warehouse to customer sites is addressed as follows. This paper adopts MATLAB R2022a for programming test. The experiment is conducted using the improved ant colony algorithm mentioned in section 4.1 with the shortest distribution path length in total and the highest load factor of each distribution vehicle.

The number of customer sites is defined as $n = 50$, and the number of ants is $m = n + 1 = 51$; The maximum capacity of each distribution vehicle is $Q = 180$, and the pheromone evaporation factor is $\rho = 0.9$. It is used to control the evaporation rate of pheromone, avoiding premature convergence to local optima. The pheromone heuristic factor is defined as $\alpha = 1$, which is used to control the relative influence of pheromone in route selection. The expected heuristic factor is defined as $\beta = 8$, which is used to control the relative influence of heuristic information (path length and load factor) on the route selection process of ants. The pheromone constant is $Q = 100$, indicating the total amount of pheromone released by ants after selecting the route.

Table 2: Coordinates and quantity demanded of customer sites

No.	X-coordinate	Y-coordinate	Quantity demanded	No.	X-coordinate	Y-coordinate	Quantity demanded
1	37	52	7	26	27	68	7
2	49	49	30	27	30	46	15
3	51	64	17	28	43	67	14
4	20	26	9	29	58	48	6
5	44	30	21	30	58	27	19
6	21	47	15	31	3	69	11
7	19	63	23	32	58	46	12
8	31	42	23	33	46	10	23
9	52	33	11	34	61	33	26
10	51	21	5	35	62	63	17
11	42	41	19	36	63	69	6
12	31	32	29	37	32	22	9
13	15	25	23	38	45	35	15
14	11	45	14	39	59	18	24
15	19	19	8	40	5	6	7
16	10	41	15	41	10	17	27
17	27	23	3	42	21	10	13
18	17	33	41	43	5	64	11
19	23	13	19	44	30	15	16
20	57	58	28	45	39	10	10
21	62	42	8	46	32	39	5
22	42	57	8	47	65	32	25
23	16	57	16	48	25	55	17
24	48	52	10	49	28	28	18
25	7	38	28	50	6	37	10

A rectangular coordinate system is established based on the relative positions of the starting point (the warehouse) and all the customer sites and a suitable origin coordinate (0,0) is selected. The warehouse is 40 kilometers (km) away from the origin coordinate both horizontally and vertically, the coordinate of which can be indicated as (40,40). The number, coordinate, and quantity demanded of the rest 50 customer sites can be found in Table 2. Both X-coordinate and Y-coordinate are measured in km, and the quantity demanded and the maximum capacity of distribution vehicles are measured by the same unit.

MATLAB R2022a is used for programming test based on the aforementioned data. Three iterations are conducted with the number of iteration being set as $Nc = 100{,}1000{,}10000$ respectively. While the number of iterations is 100, products will be distributed by five vehicles. Vehicle No.1 departs from the starting point (the warehouse) and sequentially passes through customer sites 11-38-5-9-30-34-47-21-32-29 with a load factor of 90%. Vehicle No.2 departs from the starting point (the warehouse) and sequentially passes through customer sites 2-24-20-35-36-3-28-22-1-27-8-46 with a load factor of 100%. Vehicle No.3 departs from the starting point (the warehouse) and sequentially passes through customers sites 12-49-17-37-19-42-15-13-4-18 with a load factor of 96%. Vehicle No.4 departs from the starting point (the warehouse) and sequentially passes through customer sites 50-25-16-14-6-48-26-7-23-43-31 with a load factor of 93%. Vehicle No.5 departs from the starting point (the warehouse) and sequentially passes through customer sites 41-40-44-45-33-39-10 with a load factor of 62%. The optimal total route length is $478.04km$. The optimal route is shown in Figure 3.

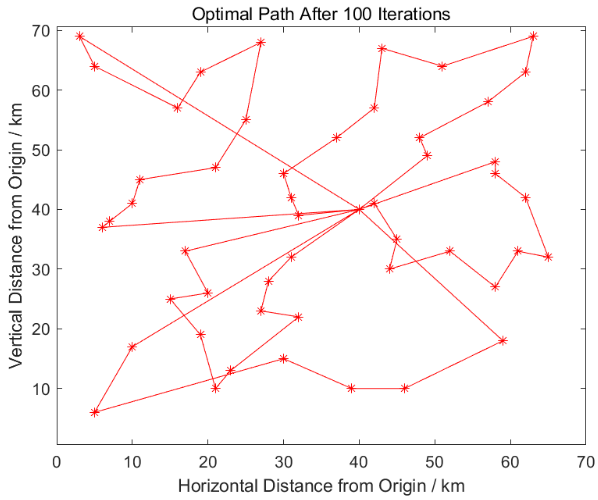

Figure 3: The optimal route after 100 iterations

While the number of iterations is 1,000, products will be distributed by five vehicles. Vehicle No.1 departs from the starting point (the warehouse) and sequentially passes through customer sites 11-38-5-9-30-10-39-47-34-21 with a load factor of 96%. Vehicle No.2 departs from the starting point (the warehouse) and sequentially passes through customer sites 32-29-24-2-20-35-36-3-28-22-1-27 with a load factor of 94%. Vehicle No.3 departs from the starting point (the warehouse) and sequentially passes through customer sites 8-46-12-49-17-37-44-45-33-42-19-15 with a load factor of 98%. Vehicle No.4 departs from the starting point (the warehouse) and sequentially passes through customer sites 4-13-18-14-16-25-50-41-40 with a load factor of 97%. Vehicle No.5 departs from the starting point (the warehouse) and sequentially passes through customer sites 6-48-7-23-43-31-26 with a load factor of 56%. The optimal total route length is $492.93km$. The optimal route is shown in Figure 4.

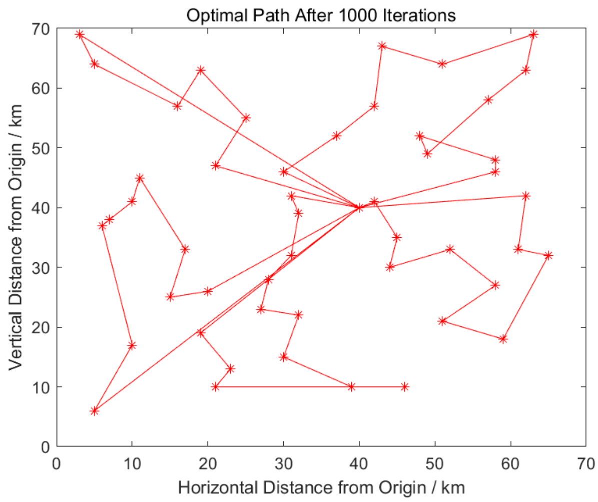

Figure 4: The optimal route after 1,000 iterations

While the number of iterations is 10,000, products will be distributed by five vehicles. Vehicle No.1 departs from the starting point (the warehouse) and sequentially passes through customer sites 11-46-8-27-1-22-28-3-20-35-36 with a load factor of 88%. Vehicle No.2 departs from the starting point (the warehouse) and sequentially passes through customer sites 2-24-29-32-21-34-47-30-9-38 with a load factor of 90%. Vehicle No.3 departs from the starting point (the warehouse) and sequentially passes through customer sites 5-37-44-19-42-15-4-13-18 with a load factor of 88%. Vehicle No.4 departs from the starting point (the warehouse) and sequentially passes through customers sites 25-50-16-14-6-48-23-7-26-43-31 with a load factor of 93%. Vehicle No.5 departs from the starting point (the warehouse) and sequentially passes through customer sites 12-49-17-41-40-45-33-39-10 with a load factor of 81%. The optimal total route length is 476.85km. The optimal route is shown in Figure 5.

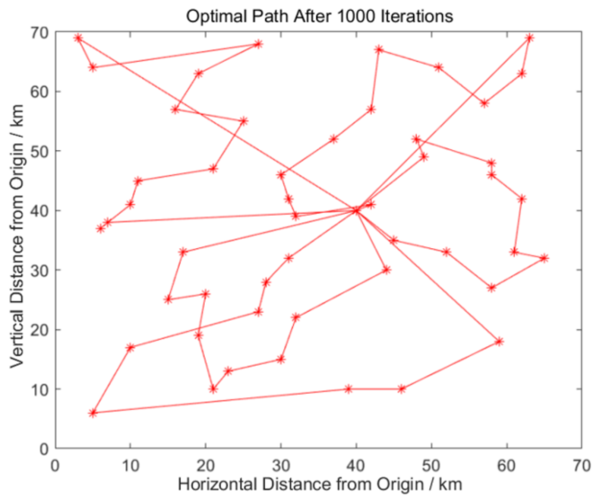

Figure 5: The optimal route after 10,000 iterations

Regarding the optimal route length, the shortest optimal route length is 476.85km when the number of iterations is 10,000. The median optimal route length is 478.04km when the number of iterations is 100. The longest optimal route length is 492.93km when the number of iterations is 1,000. Regarding the load factor of distribution vehicles, there is one distribution vehicle with a load factor of 62% and 56% respectively, when the number of iterations is 100 and 1,000, both below 70%. The load factors of all distribution vehicles are higher than 80% when the number of iteration is 10,000. In summary, the results of 10,000 iterations are better than the results of 100 iterations and 1,000 iterations from the two aspects aforementioned. Therefore, the optimal route length is $476.85km$, and the optimal routes are 11-46-8-27-1-22-28-3-20-35-36, 2-24-29-32-21-34-47-30-9-38, 5-37-44-19-42-15-4-13-18, 25-50-16-14-6-48-23-7-26-43-31, and 12-49-17-41-40-45-33-39-10.

5. Conclusion

This paper has improved the traditional ant colony algorithm while finding the optimal route of direct distribution from fresh food e-commerce warehouses to customer sites. In addition to the total length of transportation, the load factor of each distribution vehicle is considered, ensuring the optimal route is superior with both the shortest route length of transportation and the maximum load factor of each vehicle. Meanwhile, this paper conducted 100, 1,000, and 10,000 iterations respectively while keeping other parameters unchanged, and the final results show that the optimal route of 10,000 iterations is superior to those of 100 and 1,000 iterations in terms of the total route length and load factor of each distribution vehicle.

This paper selects a random period to analyze the channel involving offline distributors. Applying mathematical knowledge, it derives a functional expression for the inventory level at a specific moment of the selected period, and thereby obtains the functional expressions for warehousing cost and deterioration cost within that period. Furthermore, the summation of warehousing cost and deterioration cost represents the cost of the channel involving offline distributors within a random period. According to the derived relations, the cost is related to the warehousing cost per unit, deterioration cost per unit, deterioration rate, and the quantity demanded. Hence, the following measures can be taken to reduce the cost: Firstly, the warehouse can update cold storage technology to reduce the warehousing cost. Secondly, e-commerce businesses can optimize the design of stock keeping unit (SKU) structure with rational planning of fresh food varieties and amounts to avoid overstocking. Thirdly, e-commerce businesses can also improve the inventory management plan, set a safety threshold for the inventory level, alert for products that fall below the threshold, and implement promotional activities to reduce the loss of deterioration.

This paper studies two distribution channels of food e-commerce business and analyses their cost optimization. Future studies, based on the channel of direct distribution from the warehouse to customer sites, may further extend the model involving low carbon, customer satisfaction, time limit, and other aspects to analyze the optimal route from perspectives of carbon cost and time limit. Regarding the channel involving offline distributors, in order to simplify the model, this paper does not consider the time for procurement and delivery. Nevertheless, fresh food e-commerce businesses need to strengthen their cooperation with fresh food suppliers, optimize the procurement process, and improve the supply chain management to ensure the freshness and quality of fresh commodities.

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